

CLAIMS

I claim:

1. A method for estimating an azimuthal dependence of a parameter of a borehole using logging sensor measurements acquired as a function of azimuth of said logging sensors, the method comprising:

(a) rotating a downhole tool in a borehole, the tool including at least one logging sensor and at least one azimuth sensor, data from the logging sensor being operable to assist determination of a parameter of the borehole;

(b) causing the at least one logging sensor and the at least one azimuth sensor to acquire at least one data pair, each data pair comprising a logging sensor measurement and a corresponding azimuth;

(c) processing a convolution of selected data pairs with a predetermined window function to determine convolved logging sensor data for at least one azimuthal position.

2. The method of claim 1, wherein the window function comprises a rectangular window function.

3. The method of claim 2, wherein the rectangular window function is expressed mathematically as follows:

$$W(\phi) = \begin{cases} 2\pi p, & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases};$$

wherein $W(\phi)$ represents the rectangular window function, p represents the
 5 number of the azimuthal positions for which convolved logging sensor data is
 determined, ϕ represents azimuth, and x represents a factor controlling an azimuthal
 breadth of the window function.

4. The method of claim 1, wherein the window function is tapered and
 symmetrical about the at least one azimuthal position.

5. The method of claim 4, wherein the window function is selected from the
 group consisting of Bartlett, Blackman, Gaussian, Hanning, Hamming, and Kaiser
 functions.

6. The method of claim 4, wherein the window function is expressed
 mathematically by an equation selected from the group consisting of:

$$(1) \quad W(\phi) = \begin{cases} 2\pi p \left(1 - \frac{p|\phi|}{x\pi}\right), & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases};$$

$$(2) \quad W(\phi) = \begin{cases} 2\pi p \left[0.42 + 0.5 \cos\left(\frac{p\phi}{x}\right) + 0.08 \cos\left(2\frac{p\phi}{x}\right)\right], & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases};$$

$$(3) \quad W(\phi) = \begin{cases} \exp\left(-\alpha_a \left(\frac{p\phi}{x\pi}\right)^2\right), & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases};$$

$$(4) \quad W(\phi) = \begin{cases} \pi p \left(1 + \cos\left(\frac{p\phi}{x}\right)\right), & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases};$$

$$(5) \quad W(\phi) = \begin{cases} 2\pi p \left[0.54 + 0.46 \cos\left(\frac{p\phi}{x}\right)\right], & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases}; \text{ and}$$

$$(6) \quad W(\phi) = \begin{cases} \frac{I_0\left(\omega_a \sqrt{1 - \left(\frac{p\phi}{x\pi}\right)^2}\right)}{I_0(\omega_a)}, & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases};$$

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wherein $W(\phi)$ represents the window function, p represents the number of the azimuthal positions for which convolved logging sensor data is determined, ϕ represents azimuth, x and ω_a and α_a represent factors controlling an azimuthal breadth of the window function, and I_0 represents a zero order modified Bessel function of the first kind.

7. The method of claim 1, further comprising:

(d) processing the convolved logging sensor data determined in (c) to determine at least one Fourier coefficient of the azimuthal dependence of the parameter.

8. The method of claim 7, further comprising:

(e) processing the at least one Fourier coefficient of the azimuthal dependence of the parameter determined in (d) to estimate a value of the parameter at an arbitrary azimuth

9. The method of claim 1, wherein the logging sensor is selected from the group consisting of a natural gamma ray sensor, a neutron sensor, a density sensor, a resistivity sensor, a formation pressure sensor, an annular pressure sensor, an ultrasonic sensor, and an audio-frequency acoustic sensor.

10. The method claim 1, wherein the parameter of the borehole is selected from the group consisting of formation density, formation resistivity, formation acoustic velocity, gamma ray interaction cross section, and neutron interaction cross section.

11. The method of claim 1, wherein the tool is coupled to a drill string.

12. The method of claim 1, wherein the tool further comprises a logging while drilling tool.

13. The method of claim 1, wherein the tool further comprises a controller, the controller disposed to cause the at least one logging sensor and the at least one azimuth sensor to acquire the plurality of data pairs in (b), the controller further disposed to determine the convolved logging sensor data in (c).

14. The method of claim 1, wherein the at least one logging sensor and the at least one azimuth sensor acquire the plurality of data pairs in (b) during rotation of the tool in (a).

15. The method of claim 1, wherein (b) further comprises causing the at least one logging sensor and the at least one azimuth sensor to acquire a plurality of data pairs during predetermined first and second time periods.

16. The method of claim 15, further comprising:

(d) assigning corresponding first and second borehole depth values to the convolved logging sensor data determined in (c) using data pairs acquired during the first and second time periods.

17. The method of claim 1, wherein a plurality of azimuthal positions in (c) are substantially evenly distributed about a circular horizon.

18. A method for forming an image of a parameter of a borehole using logging sensor measurements acquired as a function of azimuth of said logging sensors, the method comprising:

(a) rotating a downhole tool at a first longitudinal position in the borehole, the tool including at least one logging sensor and at least one azimuth sensor, data from the logging sensor being operable to assist determination of a parameter of the borehole;

(b) causing the at least one logging sensor and the at least one azimuth sensor to acquire at least one data pair, each data pair comprising a logging sensor measurement and a corresponding azimuth;

(c) processing a convolution of selected data pairs with a predetermined window function to determine convolved logging sensor data for at least one azimuthal position;

(d) repositioning the downhole tool and rotating it at a second longitudinal position in the borehole and repeating (b) and (c).

19. The method of claim 18, further comprising:

(e) transmitting the convolved sensor data determined in (c) and (d) uphole.

20. The method of claim 18, further comprising:

(e) assigning a first depth value to the convolved sensor data determined in (c) and a second depth value to the convolved sensor data determined in (d).

21. The method of claim 18, wherein the window function comprises a rectangular window function.

22. The method of claim 18, wherein the window function is tapered and symmetrical about the at least one azimuthal position.

23. The method of claim 18, wherein the window function is selected from the group consisting of Bartlett, Blackman, Gaussian, Hanning, Hamming, and Kaiser functions.

24. The method of claim 18, further comprising:

(e) processing the convolved sensor data determined in (c) and (d) to determine at least one Fourier coefficient of an azimuthal dependence of the parameter.

25. The method of claim 24, further comprising:

(f) processing the at least one Fourier coefficient of the azimuthal dependence of the parameter determined in (e) to estimate a value of the parameter at an arbitrary azimuth.

26. The method of claim 18, wherein the logging sensor is selected from the group consisting of a natural gamma ray sensor, a neutron sensor, a density sensor, a resistivity sensor, a formation pressure sensor, an annular pressure sensor, an ultrasonic sensor, and an audio-frequency acoustic sensor.

27. The method claim 18, wherein the parameter of the borehole is selected from the group consisting of formation density, formation resistivity, formation acoustic velocity, gamma ray interaction cross section, and neutron interaction cross section.

28. The method of claim 18, wherein the tool is coupled to a drill string.

29. The method of claim 18, wherein the downhole tool further comprises a logging while drilling tool.

30. A system for estimating an azimuthal dependence of a parameter of a borehole using logging sensor measurements acquired as a function of azimuth of said logging sensors, the system comprising:

a downhole tool including at least one logging sensor and at least one azimuth sensor, data from the logging tool being operable to assist determination of a parameter of the borehole, the downhole tool further including a controller disposed to convolve logging sensor data with a predetermined window function, the downhole tool operable to be coupled to a drill string and rotated in a borehole;

the controller configured to:

(A) cause the at least one logging sensor and the at least one azimuth sensor to acquire at least one data pair, each data pair comprising a logging sensor measurement and a corresponding azimuth; and

(B) process a convolution of selected data pairs with a predetermined window function to determine convolved logging sensor data for at least one azimuthal position.

31. The system of claim 30, wherein the window function is expressed mathematically by an equation selected from the group consisting of:

$$(1) \quad W(\phi) = \begin{cases} 2\pi p, & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases}$$

$$(2) \quad W(\phi) = \begin{cases} 2\pi p \left(1 - \frac{p|\phi|}{x\pi}\right), & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases};$$

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$$(3) \quad W(\phi) = \begin{cases} 2\pi p \left[0.42 + 0.5 \cos\left(\frac{p\phi}{x}\right) + 0.08 \cos\left(2\frac{p\phi}{x}\right) \right], & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases};$$

$$(4) \quad W(\phi) = \begin{cases} \exp\left(-\alpha_a \left(\frac{p\phi}{x\pi}\right)^2\right), & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases};$$

$$(5) \quad W(\phi) = \begin{cases} \pi p \left(1 + \cos\left(\frac{p\phi}{x}\right)\right), & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases};$$

$$(6) \quad W(\phi) = \begin{cases} 2\pi p \left[0.54 + 0.46 \cos\left(\frac{p\phi}{x}\right) \right], & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases}; \text{ and}$$

$$(7) \quad W(\phi) = \begin{cases} \frac{I_0\left(\omega_a \sqrt{1 - \left(\frac{p\phi}{x\pi}\right)^2}\right)}{I_0(\omega_a)}, & |\phi| < \frac{x\pi}{p} \\ 0, & \frac{x\pi}{p} \leq \phi < \pi \\ 0, & -\pi \leq \phi \leq -\frac{x\pi}{p} \end{cases};$$

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wherein $W(\phi)$ represents the window function, p represents the number of the azimuthal positions for which convolved logging sensor data is determined, ϕ represents azimuth, x and ω_a and α_a represent factors controlling an azimuthal breadth of the window function, and I_0 represents a zero order modified Bessel function of the first kind.

32. A computer readable medium storing a software program, the software program configured to enable a processor to perform a method for estimating an azimuthal dependence of a parameter of a borehole using logging sensor measurements acquired as a function of azimuth of said logging sensors, the method comprising:

5 (a) causing at least one logging sensor and at least one azimuth sensor deployed on a downhole tool to acquire at least one data pair, each data pair comprising a logging sensor measurement and a corresponding azimuth;

(b) processing a convolution of selected data pairs with a predetermined window function to determine convolved logging sensor data for at least one azimuthal position.

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33. The computer readable medium of claim 32, wherein the window function is tapered and symmetrical about the at least one azimuthal position.

34. The computer readable medium of claim 32, wherein the window function is selected from the group consisting of rectangular, Bartlett, Blackman, Gaussian, Hanning, Hamming, and Kaiser functions.

35. The computer readable medium of claim 32, wherein (a) further comprises causing the at least one logging sensor and the at least one azimuth sensor to acquire at least one data pair during predetermined first and second time periods.

36. The computer readable medium of claim 35, wherein the method further comprises:

(c) assigning corresponding first and second borehole depth values to the convolved logging sensor data determined in (b) using data pairs acquired during the first and second time periods.

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37. The computer readable medium of claim 32, wherein the method further comprises:

(c) processing the convolved logging sensor data determined in (b) to determine at least one Fourier coefficient of the azimuthal dependence of the parameter.

38. The computer readable medium of claim 37, wherein the method further comprises:

(d) processing the at least one Fourier coefficient of the azimuthal dependence of the parameter determined in (c) to estimate a value of the parameter at an arbitrary azimuth.